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Probe-Based Micro-Scale Manipulation and Assembly Using Force Feedback

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Abstract - Repeatable manipulation and assembly of micro-scale components is a critical capability for future developments in opto-electronics, hybrid microelectromechanical systems, and the integration of nano-scale devices into larger systems. This paper focuses on one particular part of this problem; the manipulation and assembly of microspheres using a single probe with force feedback. A sharp probe combined with a high precision positioning system is used to push microspheres into desired locations and configurations within a two-dimensional workspace. A description of this micromanipulation system is presented along with a discussion on the basic manipulation capabilities. Force feedback has been utilized in two ways. First, it is used to measure the interaction forces during micromanipulation for detecting collisions with particles and determining the forces necessary for successful manipulation. Second, a force control system for the vertical contact force has been developed for improved sensitivity during manipulation. In both cases, a piezoresistive silicon cantilever micro force sensor with an approximate force resolution of 10 μN is used. Preliminary experimental results for the force control system and the measurement of manipulation contact forces are presented.

I. INTRODUCTION

The manipulation and assembly of micro-scale components with ultra-precision positioning resolution is required in a number of manufacturing applications including opto-electronics and microelectromechanical system (MEMS). Although manufacturers strive to develop processes which minimize the need for assembly in the production of micro-scale systems, there are a number of areas where assembly is currently necessary. This is particularly true for the integration of optics and photonics with silicon-based MEMS. The spectrum of micro-scale manipulation and assembly tasks is quite large and must be broken down according to performance requirements, levels of dexterity, and application-dependent challenges. In this paper, we examine a subset of this problem, probe-based micro-scale manipulation and assembly of microspheres. There are a number of applications which can benefit from this approach including manipulating micro-optics. Additionally, basic research on probe-based micromanipulation will benefit more complex microassembly problems through the development of low-level manipulation primitives.

The use of a probe to manipulate micro-scale components has been studied by several researchers, where a probe is defined as a pointed cantilever structure with a tip radius that is significantly smaller than the components to be manipulated. Components on the order of 500 μm have been aligned using a force controlled pushing method developed by Zesch and Fearing [1]. Saito et al. [2] have demonstrated the manipulation of microspheres inside a scanning electron microscope (SEM) using a pick and place operation based on a model of the adhesion between the probe and the microspheres. This approach was incorporated into an image-based autonomous system that is capable of assembling lines of microspheres [3]. A similar manipulation method based on a model of adhesion with the addition of a high acceleration impulse used to guarantee release of the particle has also been demonstrated [4,5]. The controlled pushing of nanoparticles with an atomic force microscope (AFM) has also been investigated, using both heuristic [6,7] and model-based [8,9] approaches.

Although these examples show that probe-based micromanipulation is a viable approach, there are still many issues that must be addressed to attain a repeatable manipulation system for manufacturing. In particular, the dependence on adhesion models is likely to cause difficulties in expanding these methods to more generic manipulation tasks. A number of researchers have developed mathematical models for the intermolecular and surface forces present during micromanipulation, including van der Waals, electrostatic, and capillary forces [10,11]. These models have been used to plan the pick and place operations for microspheres [12,13] as well as more generic objects [14]. However, these models have a large amount of uncertainty due to variations in system parameters (material properties, temperature, humidity, etc.), part geometry, and contamination. Furthermore, the electrostatic force is very difficult to predict since the electrical charge on the surface of a micro-scale component is not known *a priori*. Therefore, although it is reasonable to use model-based approaches in micromanipulation, a complete dependence on these models is likely to result in poor performance due to their uncertainty.

One possible solution to these problems with model-based micromanipulation is the use of force measurements to identify some of the critical parameters within the intermolecular and surface force models. A set of measurements prior to the intended manipulation procedures could be used to independently determine the dominant forces for the given conditions. For example, it may be found that the electrostatic force is very small when manipulating gold particles on a grounded substrate. The adhesion models could then be modified according to the identified parameters and the relative importance of each of the components.

This paper presents initial steps in developing a micromanipulation system that can measure the micro-scale contact forces during manipulation and actively control the contact force. These two capabilities will clarify the dynamics of micromanipulation and improve the manipulation repeatability and generality. Many of the micromanipulation systems discussed above have included a force sensor [1-9], but very few have addressed the issue of force control. Most recently, Shen et al. [15,16] have demonstrated micro-scale force control using a novel sensor but did not apply it to micromanipulation directly.

In the following section, the micromanipulation system used for these experiments will be presented. The micromanipulation capabilities of this system will then be discussed. This is followed by a description of the micro force sensor and its calibration. Experimental measurements of contact forces during manipulation of microspheres are then presented. Finally, the force control system is described and experimental force regulation results are discussed.

II. MICROMANIPULATION SYSTEM

The micromanipulation system used in the experiments presented in this paper is designed specifically for basic research on probe-based micromanipulation. A 2-D representation of the system is shown in Fig. 1. A slide which has microspheres laying on it sits on top of a manual *XYZ* positioning stage. This positioning stage is used to locate a desirable batch

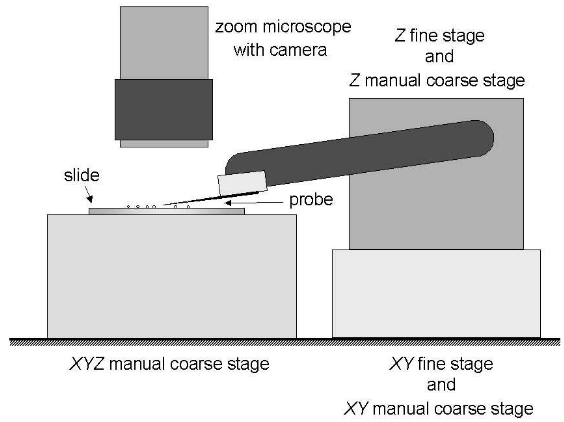


Fig. 1 Layout of the micromanipulation system (side view)

of microspheres within the field of view. A zoom microscope (140 X max. magnification) with a digital camera is located above the slide, which provides the manipulation top view. A second zoom microscope (14 X max. magnification) with a digital camera is placed horizontally (not shown in Fig. 1), in order to obtain a side view. Both digital cameras are fed into a personal computer for video rate visual feedback.

The positioning stage shown on the right side of Fig. 1 has three degrees-of-freedom (DOF) of fine motion based on piezoelectric actuators and three DOF of manual coarse motion (Burleigh MIS-5000[1]). The fine motion is controlled by a joystick, providing telemanipulation capabilities. A cantilevered arm attached to this stage holds a tungsten probe, with a tip radius smaller than 10 μm, in a clamp. An additional 3 DOF piezoelectric nanopositioning stage (Physik Instrumente Nanocube) is used to replace the manual *XYZ* positioning stage that holds the slide for the force control experiments. This nanopositioning stage has an open control architecture and is therefore better suited for these experiments. Using the visual feedback and the Burleigh joystick, interacting with microspheres is very straightforward. However, dexterous manipulation of these particles requires significant practice.

III. MANIPULATION CAPABILITIES

The nearly horizontal probe configuration, as shown in Fig. 1, was chosen over a vertical configuration due to a few factors. Most importantly, it is difficult to visualize

[1] Certain commercial products and processes are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products and processes identified are necessarily the best available for the purpose.

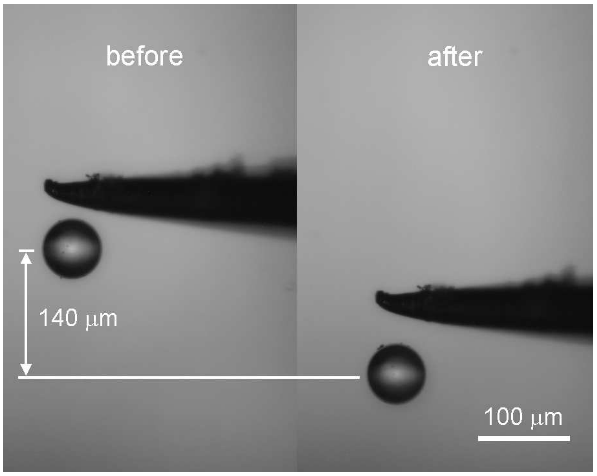


Fig. 2 Pushing using the side of the probe (before and after)

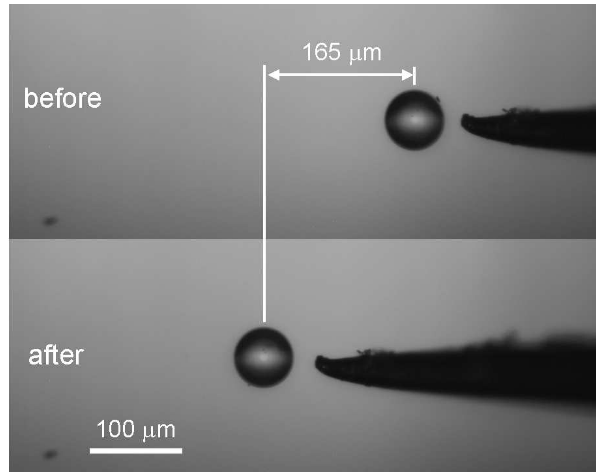


Fig. 3 Pushing using the tip of the probe (before and after)

a vertical probe in the top view microscope. Also, performing pick and place operations using a vertical probe has been found to be more challenging compared to the nearly horizontal configuration. The main drawback of the nearly horizontal configuration is that 2-D manipulations are constrained to be unidirectional along one DOF, which will be discussed shortly. The general manipulation maneuvers possible with the proposed micromanipulation system are pushing with the side of the probe; pushing with the tip of the probe; and pick and place operations using the tip of the probe, as discussed below.

III.A. Pushing Using the Side of the Probe

The simplest maneuver using the proposed micromanipulation system is to push a microsphere using the side of the probe. In this case, the probe is positioned on the side of a microsphere with a height equal to the center of the microsphere. The probe then moves towards the microsphere, contacts with the microsphere and continues until the desired position is reached. The probe is then moved in the reverse direction to release the microsphere. This process is shown in Fig. 2, where a 65 μm microsphere is moved 140 μm. In all experiments, the microspheres are made of polymethyl-methacrylate (PMMA) and have a diameter range of 30 μm to 75 μm.

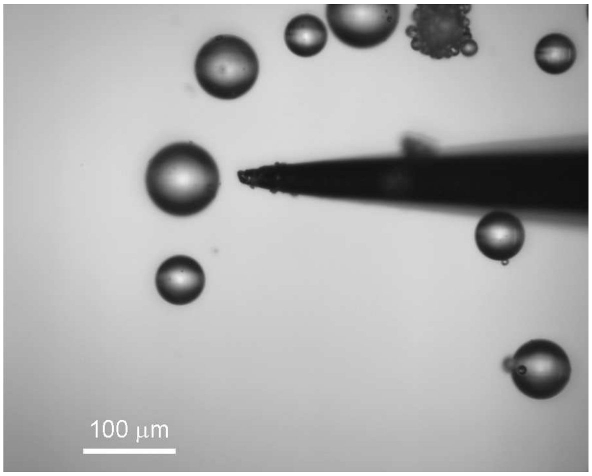
III.B. Pushing Using the Tip of the Probe

Pushing with the tip of the probe requires the probe tip to be aligned with the center of the microsphere, again at a height equal to the microsphere center. The probe is then moved forward, along its axial direction, to contact the microsphere. Continuing motion along this axis will move the microsphere. The probe is stopped at the desired location and retracted to release the microsphere. This operation is shown in Fig. 3, where a 65 μm microsphere is pushed 165 μm with the probe tip. Unlike pushing with the side of the probe, pushing with the tip of the probe along the probe axis is not always straightforward. One problem is that the position of the microsphere at the tip is not stable. The center of the microsphere can easily move off of the probe center axis, causing a moment on the microsphere. Continuous adjustments of the probe position with respect to the microsphere center are necessary for successful manipulation. This operation would be particularly difficult to automate, although it is certainly possible.

Another obvious problem is that the microsphere can only be moved in one direction using this approach (to the left in Fig. 3). This is typically solved with the use of more complex and less deterministic approaches such as touching the probe to the top of the microsphere to make it roll backwards or using the side of the probe to drag it. The pick and place operation discussed in the next subsection can also be used. However, with clever planning and proper utilization of the microspheres, it is often possible to only use pushing operations for planar patterns. Only pushing operations were used to form a line of microspheres, as shown in Fig. 4. This process can be very tedious but it demonstrates the basic capabilities which enable the assembly of a number of different patterns of microspheres.

III.C. Pick and Place

The operations discussed in the previous two subsections are very useful but are limited to manipulation within a 2-D workspace. However, it is possible to pick microspheres up off of the slide and then place them in another location using only the probe, as discussed in [2-5]. In this subsection, we discuss the procedure for pick and place operations using our micromanipulation system.



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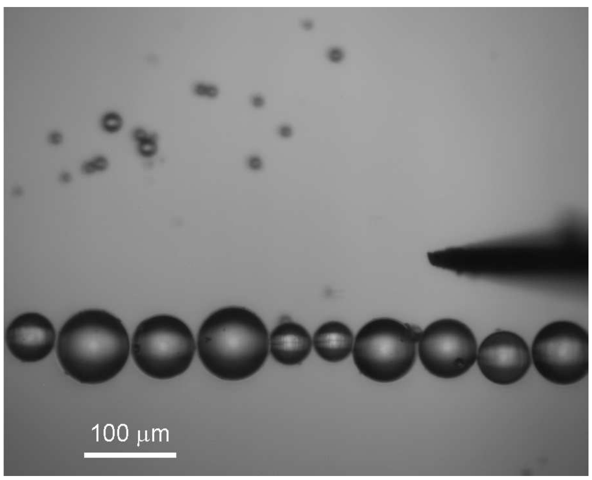


(b)

Fig. 4. Manipulating microspheres into a line: a) original configuration, and b) the completed line.

The pick and place operation is shown in steps in Fig. 5. First, the probe is positioned above the microsphere (Fig. 5a). The probe is then moved down until it comes into contact with the microsphere close to the tip of the probe. It is desirable to have the contact be near the tip but not exactly at the tip so that the surface area of the contact is increased. Next, the probe is pushed harder into the microsphere and then the probe is moved upward. If the conditions are favorable, the microsphere remains in contact with the probe and lifts off of the slide (Fig. 5b). The effectiveness of this step can vary from microsphere to microsphere, and has been found to change due to temperature, particularly with respect to the heating caused by the microscope illumination. After the microsphere is lifted off of the surface, the probe is positioned above the desired location (Fig. 5c).

The final step in this operation, the placement of the microsphere on the surface, is the most difficult. Typically, if the probe is lowered to bring the microsphere

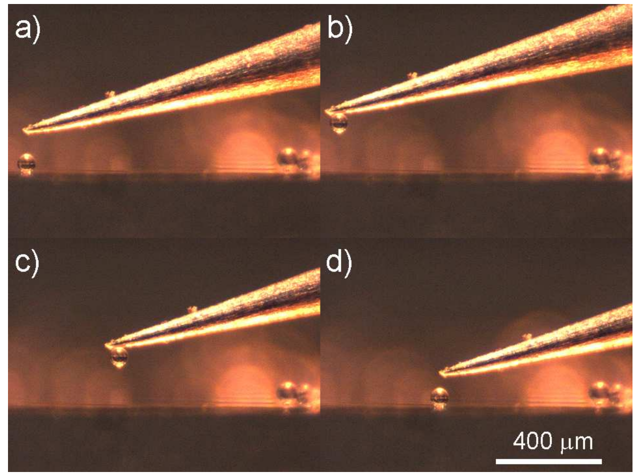


Fig. 5 Pick and place operation: a) position above microsphere, b) press down on microsphere and then pick up, c) move to desired location, and d) place on substrate and release.

into contact with the substrate and then raised again, the microsphere will remain stuck to the probe. Therefore, a heuristic approach for releasing the microsphere has been adopted, partially based on the methods discussed in [2-5]. A reduction in the contact surface area will result in a reduction of the intermolecular and surface forces, particularly for van der Waals and electrostatic forces. In this case, the surface area can be reduced by sliding the microsphere to the tip of the probe and then trying to release it. The microsphere is moved to the tip by simultaneously moving the probe down and to the side (in this case, to the right) while the microsphere is in contact with the surface. When the microsphere reaches the tip, the probe is then only moved to the side and the microsphere is released. This maneuver requires practice but can be very repeatable. The released particle can be seen in Fig. 5d.

III.D. Discussion

Three different manipulation methods have been discussed in the previous subsections, which when combined can provide a very versatile micromanipulation system. There are a number of MEMS manufacturing applications which would benefit from these capabilities. Integrating high quality micro-optics, such as micro ball lenses, into MEMS is one difficult manufacturing problem that could be solved. There are also several hazardous environment applications in which micromanipulation would be an excellent option. Nuclear micro-batteries are currently being developed for powering MEMS in remote locations. The radioactive microspheres that will be used in these batteries can be manipulated and assembled, eliminating human exposure. Similarly, the radioactive seeds used for the treatment of certain types of cancer could be sorted and packaged autonomously. This will be particularly important as the size of these seeds is reduced for more localized tumor treatment.

The micromanipulation operations presented in this section have been completed using telemanipulation with only visual feedback (top and side views) to guide the user. Our future goal is to automate these operations in order to fully realize the benefits of micromanipulation. In the following sections, the integration of force feedback into this system will be discussed, providing a prerequisite capability for fully autonomous micromanipulation.

IV. PROBE WITH FORCE SENSOR

Although a number of micro force sensors have been described in the literature, there are very few options that are commercially available. In particular, it is difficult to find a sensor with dimensions suitable for placing it at the end of a micromanipulator and attaching a tungsten probe. Many of the force sensors used in micromanipulation have macro-scale dimensions, making placement near the tip impossible [2,3]. In this research, the SensorOne AE801 micro force sensor has been adopted. The AE801 is a silicon cantilever which has two doped piezoresistive strain gages, one on each side of the beam. The strain caused by a load on the beam is measured by combining the two piezoresistors with two gauge resistors in a Wheatstone bridge configuration. The bridge output voltage is then amplified using a standard strain gauge amplifier.

The micro force sensor was adapted for micromanipulation by first attaching a tungsten probe and then calibrating the sensor. The probe was bonded to the end of the sensor using an acrylic structural adhesive. A diagram of the assembled sensor with probe is shown in Fig. 6. Additionally, Fig. 6 describes the basic method for calibrating the sensor. Several masses were fabricated from stainless steel wire and calibrated using a high precision scale. A mass guide was then used to position each of the calibrated masses over the micro force sensor and subsequently lower the mass onto the sensor using tweezers. The micro force sensor was calibrated at the tip of the cantilever while the probe was attached using 300 mg, 400 mg, and 500 mg masses. The results from this calibration are shown in Fig. 7, where the bridge excitation voltage was 5 V. The sensitivity of the sensor was found to be 44.54 V/N.

This calibration was performed at the end of the cantilever, rather than at the tip of the probe, to avoid damage to the probe tip. However, the sensitivity of the sensor at the probe tip can be estimated based on two parameters, the distance between the end of the cantilever and the cantilever support (l_1), and the distance between the probe tip and the cantilever support (l_2). For a load

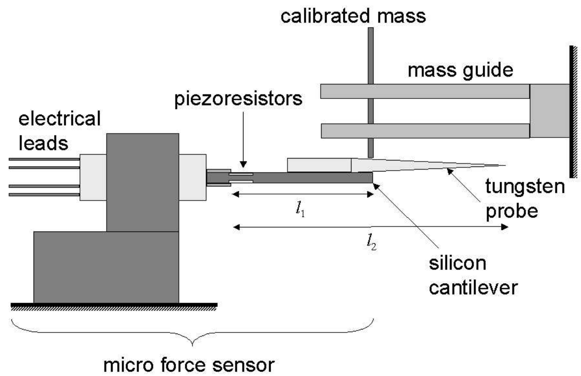


Fig. 6 Schematic of the force sensor with a mounted probe and the sensor calibration fixture

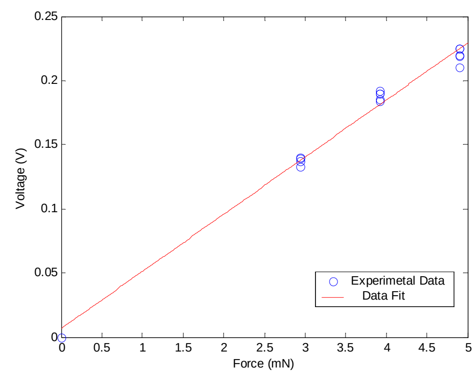


Fig. 7 Calibration data for the micro force sensor with the probe attached

applied at l_1, the displacement of the beam is proportional to the cube of l_1. Therefore, it can be shown that the sensitivity at the probe tip can be approximated by multiplying the sensitivity found at the end of the cantilever by the cube of the ratio of l_2/l_1, which in this case results in an increase in sensitivity by a factor of eight. The sensitivity at the probe tip is therefore approximated by 356.32 V/N. Based on this sensitivity and the resolution of a 16 bit A/D converter, the expected force resolution is on the order of 10 µN or less.

V. MANIPULATION FORCE MEASUREMENT

There are a number of manipulation maneuvers in which measuring the contact force would improve dexterity and provide information on the interaction dynamics. One application is its use in a collision detection scheme for automated manipulation. It can also be used to measure the force necessary for the pick and place operation previously discussed. The maximum force necessary for gaining the proper level of adhesion to lift an object can be measured and then used in later

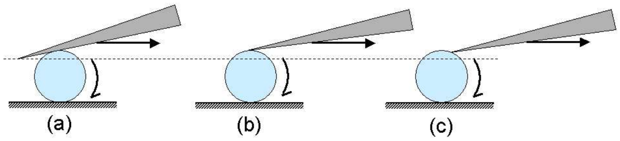


Fig. 8 Rolling a microsphere with the probe tip

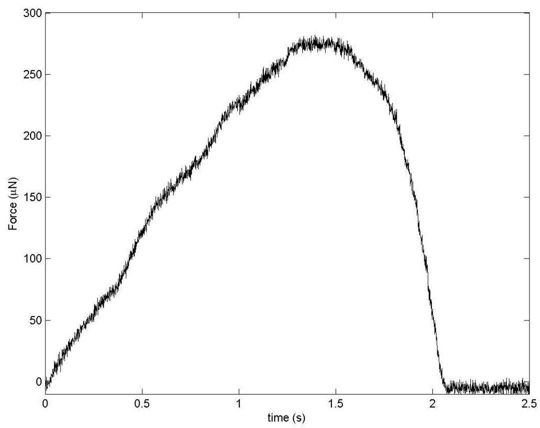


Fig. 9 Vertical force while rolling a microsphere

operations. Similarly, the force profile while releasing a microsphere can be measured and then utilized for an open-loop heuristic controller. Finally, we believe that improvements in the sensitivity of the force sensor would enable the characterization of intermolecular and surface forces between the probe and the microspheres. These measurements would be very useful in developing proper assembly plans.

In this paper, we demonstrate one application of measuring the contact force during manipulation. The probe can be used to roll a microsphere by placing the tip on the top of the microsphere and then moving the probe parallel to the substrate. This maneuver is described in Fig. 8. First, the tip of the probe is placed to the left of the microsphere (Fig. 8a). Then the probe is moved to the right, eventually contacting with the microsphere, causing a contact force. As the probe continues to the right, the microsphere will begin to roll due to friction and the probe tip will move vertically towards the apex of microsphere (Fig. 8b). Finally, the probe tip will move down the side of the microsphere and the contact force will approach zero (Fig. 8c). If the height of the probe is initially too low, the microsphere will not roll, but instead be dragged. As a demonstration of the microsphere rolling principle, the contact force while rolling has been measured, as shown in Fig. 9. The force profile during this maneuver is quite intuitive, the force increases while the tip approaches the apex of the microsphere, and then falls off at the end. The maximum force in this case was 270 μN. This experiment can be used in the future to determine the maximum contact force at which rolling still occurs and can be used for planning manipulation operations.

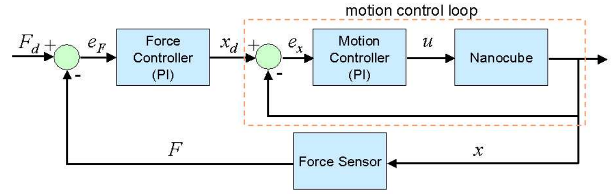


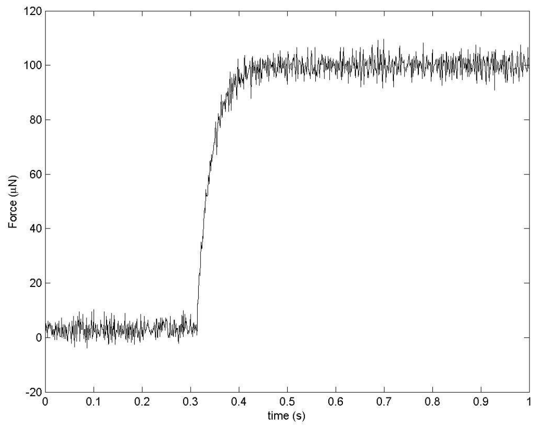
Fig. 10 Force control block diagram

VI. VERTICAL FORCE CONTROL

In the previous section, the use of force feedback was discussed as a metrology tool which can be used to improve manipulation maneuvers via better understanding of the contact forces involved. Another obvious approach, which potentially has larger implications, is the implementation of force controlled micromanipulation. In this section, the force control of the vertical contact force between the probe and a microsphere is discussed.

The control method used for force control is based on the nested motion/force loops discussed in [17], and applied to the micro-scale force control problem in [18]. A block diagram of this control method is shown in Fig. 10. A motion control loop is first established which provides the suitable motion performance necessary for the application. In this case, the motion stage being controlled is a Physik Instrumente Nanocube. For these experiments, this stage replaced the manual stage used to hold the slide with the microspheres, shown in Fig. 1. The motion controller was supplied by the manufacturer. A second feedback loop is built around the motion control loop which uses the measured contact force for feedback. Based on [17], the force controller used in this case was a simple proportional-integral (PI) control law. The controller gains were tuned to provide quick convergence to the desired contact force without any overshoot. This force control loop was implemented using a personal computer with the LabView software package and data acquisition hardware. Although this system does not provide a real-time control system, it was found to be suitable for these experiments. The sampling rate of the control loop used in all of the experiments was approximately 1 kHz.

One use for force control is to guide the probe into contact with a microsphere and then maintain a constant contact force. The results from such an operation can be seen in Fig. 11. The probe was placed above a microsphere with an approximate gap between the tip and the top of microsphere of 13.4 μm. When the controller is turned on, the contact force is zero, causing the Nanocube to move upward, as shown in the position data in Fig. 11b. After approximately 0.32 seconds, the probe makes contact with the microsphere without any significant spike in the contact force. The Nanocube then continues to move up until the desired force of 100 μN is reached,



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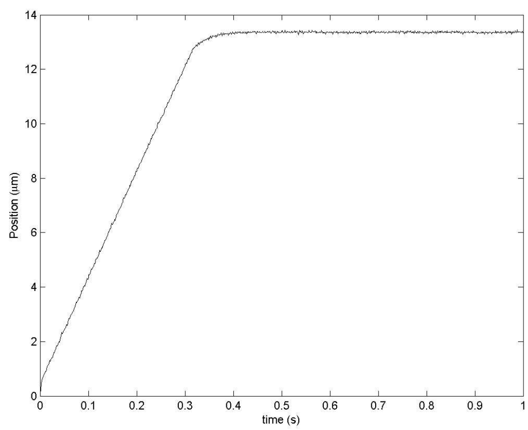
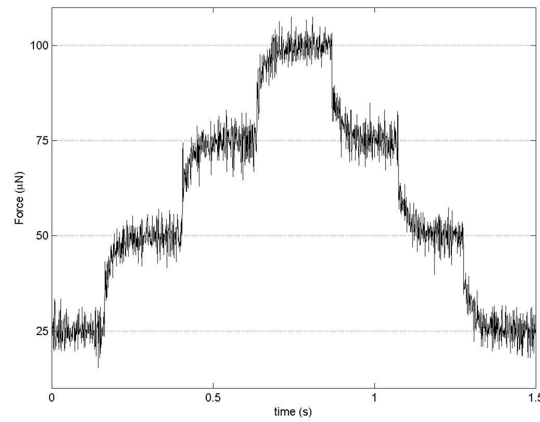


(b)

Fig. 11 Force controlled contact with a microsphere: a) contact force, b) position of nanopositioner

around 0.4 seconds, after which the desired force is then effectively regulated.

The resolution of the force control appears to be limited by the force sensor noise, rather than the control system. The standard deviation of the force sensor signal was found to be 2.54 μN and the signal fluctuations are typically bounded by ± 8 μN. Therefore, controlled force steps on the order of 10 μN can be discerned. As a demonstration, force tracking of 25 μN steps in the contact force are shown in Fig. 12. It is clear that the desired force profile can be followed with high precision. Looking at the motion data while force tracking, each 25 μN force step requires a motion step of approximately 170 nm. Based on this it is clear that for our micromanipulation system micro-scale force control requires nano-scale motion control, indicating that many DC motor stages would not be appropriate for this application. We have also used the force controller to maintain a constant contact force while a microsphere is rolled with the probe tip, although experimental results



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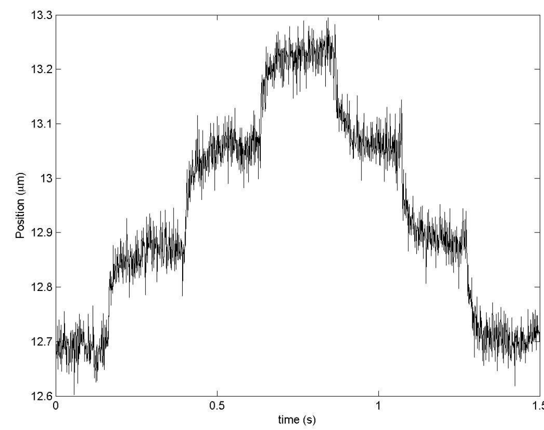

(b)

Fig. 12 Force tracking while in contact with a microsphere: a) contact force, b) position of nanopositioner

are not shown here. This capability will be particularly useful in automatically releasing microspheres.

VII. CONCLUSIONS

The manipulation of microspheres using a probe-based approach has been explored in this paper. The presented micromanipulation system has been used to demonstrate teleoperated manipulation of microspheres using three operations, pushing with the side of the probe; pushing with the tip of the probe; and pick and place. A force sensor has been integrated into the micromanipulation system for measuring contact forces during operation. This sensor has been used to determine the approximate contact forces while rolling a microsphere. Force control has also been demonstrated, including micro Newton force regulation in the vertical direction and tracking of desired force profiles. This force control system will be combined with image processing and a path planning algorithm to develop a fully autonomous micromanipulation system based on the operations discussed in this paper.

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